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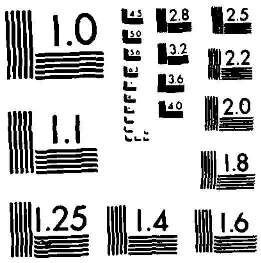

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DESIGN DEVELOPMENT AND DURABILITY VALIDATION OF POSTBUCKLED COMPOSITE AND METAL PANELS

TECHNOLOGY ASSESSMENT

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Northrop Corporation
Aircraft Division
One Northrop Avenue
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SEPTEMBER 1985

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FLIGHT DYNAMICS LABORATORY
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NOTICE

This technical report has been reviewed and is approved for publication.

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The objective of this ongoing program is to develop design procedures and life prediction methods for curved metal and composite panels designed to operate in the postbuckling regime under the action of combined compression and shear loads. In Task I of the program, the available data base was critically examined to assess the durability and damage tolerance of postbuckled structures. In this technology assessment, data relevant to the effects of combined loads, reversed loads, environment, spectrum fatigue, defects, repair methods, and stiffener attachment methods on the durability of postbuckled panels were collected and analyzed. The results were used to identify the data gaps that need to be filled and the tests that need to be performed in the program. In this report, the technology assessment and the data gaps are documented.

From the technology assessment presented in this report, it is shown that the durability and damage tolerance of postbuckled composite panels are of no concern for operating

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strain levels of 2500 μ in/in to 3000 μ in/in that are typical of stiffness critical designs. Metal panel fatigue life was found to be considerably lower than for composite panels designed to the same loading conditions. Thus, durability considerations may be the design drivers for metal panels. The available data also showed that repair techniques for composite buckling resistant structures can be successfully used to repair post-buckled composite panels and can restore panel strength to almost 100 percent of its undamaged strength.

The most significant data gap was found in the area of metal panel fatigue under combined loading. Test data and a life prediction methodology for curved metal panel designs need to be developed.

PREFACE

The work documented in this report was performed by Northrop Corporation, Aircraft Division, Hawthorne, California, in the period from September 1984 to September 1985 under USAF Contract F33615-84-C-3220. Capt. M. Sobota was the Air Force Program Monitor from September 1984 to May 1985. Dr. G.P. Sendeckyj is the current Air Force Program Monitor.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

In order to establish the viability of postbuckled structural design applications in future aerospace vehicles, an assessment of the current technology was conducted. The results of this technology assessment were utilized in identifying additional developments necessary prior to efficient application of the design concept. An extensive review of the available static and fatigue analysis methods for postbuckled structures is documented in Reference 1. The specific objective of this effort was to critically review the available data base on postbuckled composite and metal structural designs, and determine its adequacy in characterizing the durability and damage tolerance of these structures.

1.2 SCOPE

Durability assessment of postbuckled structures was conducted by reviewing the results of several preliminary design studies and test programs where fatigue tests were conducted under shear, compression or combined loading. In particular, the data were used to establish the influence of reversed loading, environment, spectrum fatigue and stiffener attachment methods on the endurance limit of flat and curved panels. Metal panel fatigue data were found to be sparse and those available were used to identify fatigue failure modes and define a stress-life diagram for metal postbuckled structures.

In evaluating the damage tolerance of composite panels, test data were used to establish the influence of impact, disbonds at the stiffener/web interface, and fastener holes on the static and fatigue response of postbuckled panels. In addition, the feasibility and integrity of conventional repairs for composite and metal panels is also demonstrated.

This technology assessment was utilized to identify gaps in the durability and damage tolerance analysis methodology and test data that need to be filled in the present program.

An extensive data base was reviewed for this assessment. The data presented in this report are a condensed version of the total data assessed and are used to illustrate the durability and damage tolerance characteristics of postbuckled composite and metal structures. A majority of the test data assessed were developed for AS/3501-6 and T300/5208 material systems. However, the results can be considered to be generally applicable to all 350°F cure epoxy systems. Section 2 details the durability characteristics of postbuckled composite and metal panels. In Section 3 the damage tolerance of composite panels is evaluated using available data. Finally, in Section 4, recommendations for future work that should be performed in this program are made on the basis of the data gaps identified from the technology assessment.

SECTION 2

DURABILITY OF POSTBUCKLED STRUCTURES

The fatigue test data generated in some of the preliminary design and test studies cited in Reference 1 provide a good insight into the durability characteristics of composite and metal postbuckled designs. In addition, these data illustrate problem areas where additional testing is essential. A summary of these data and their significance are discussed in the following paragraphs.

2.1 COMPOSITE PANELS

The available fatigue test data for composite panels under compression, shear or combined loads indicate that these panels are, in general, extremely durable. The fatigue response of flat stiffened composite shear panels is summarized in Figure 2.1. These data were obtained from tests on two different specimen designs (References 2 through 6) and include results for fully reversed constant amplitude shear loading (R = -1) as well as spectrum fatigue loading. In Figure 2.1 it can be seen that the spectrum fatigue life is considerably longer than the constant amplitude fatigue life; this illustrates the relatively high severity of constant amplitude loading. Panel fatigue failures in all tests represented in Figure 2.1, excluding the run-outs, occurred by separation of the stiffeners from the skin. The test data from Reference 5 appear to be the lower bound for the fatigue data. In addition, for these latter tests the R-ratio was 0.1 as opposed to the fully reversed shear loading applied in the case of Reference 3 panels. The lower fatigue lives obtained in Reference 5 tests, therefore, are inconsistent with the R-ratio effect observed in buckling resistant composite panels. However, the relatively steep S-N curve for the Reference 5 test data was found to be a characteristic of the stiffener/skin attachment design used for these panels. In these panels, the stiffeners were cocured with the skin and no ply drop-offs were included to ensure a smooth transition from the stiffener flange to the skin.

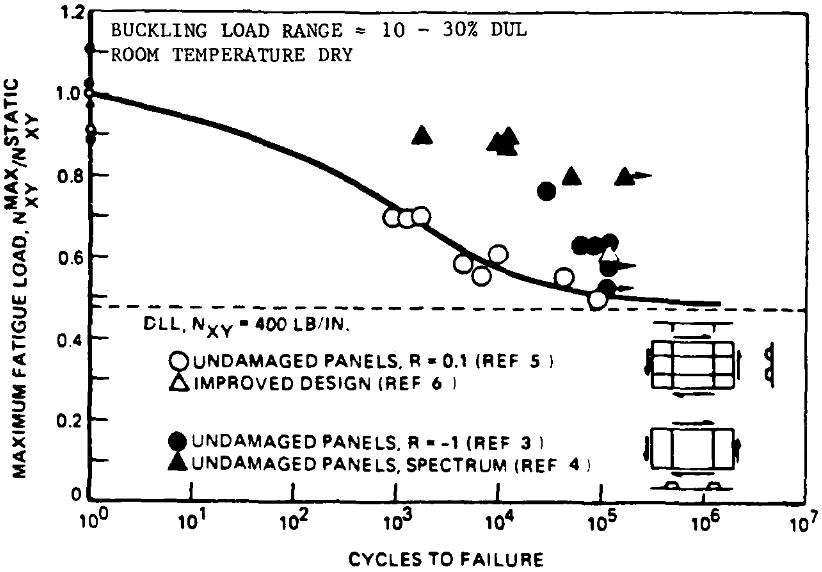

Figure 2.1. Composite Shear Panel Fatigue Response

This influence of the stiffener-skin attachment design on the fatigue response was verified by tests in Reference 6 where several alternate attachment concepts were evaluated for static strength. The test data from this study are summarized in Figure 2.2 which shows the various designs investigated as well as the static test results. From among these alternate designs, the tailored flange and the stitched untapered flange (baseline design of Reference 5 with stitching) designs were incorporated in flat shear panels that were tested in fatigue. Both design concepts resulted in higher fatigue life as indicated in Figure 2.1 by the data point corresponding to "improved design." Thus, the stiffener skin attachment design change results in a fatigue response consistent with that measured in References 3 and 4.

From the pooled flat shear panel fatigue data shown in Figure 2.1, it is evident that the fatigue endurance limit is at least the design limit load. In all these designs, the panels were prevented from buckling during the level flight condition of a typical V/STOL aircraft. The requirement of minimum skin gage resulted in panel failure loads being much greater than the required ultimate load, a condition which is typical in most aircraft applications.

The constant amplitude fatigue behavior of curved composite shear panels was investigated in Reference 1. These data are shown plotted as a function of the maximum fatigue load normalized by the static strength in Figure 2.3. The curved panel failures under fatigue loading occurred by stiffener/web separation. The endurance limit for these panels is approximately 55 percent of the static strength and is considerably in excess of the design limit load.

The fatigue response of composite compression panels is summarized in Figure 2.4. These data were obtained from tests conducted in References 1, 7, and 8 on flat and curved hat stiffened AS/3501-6 graphite/epoxy panels. The R-ratios in the fatigue tests ranged from 6 through 10. The dominant failure mode in these fatigue tests was initiation and propagation of a disbond at the skin and stiffener interface. The data indicate that an extremely long fatigue life can be expected for design limit strain levels of 2,500

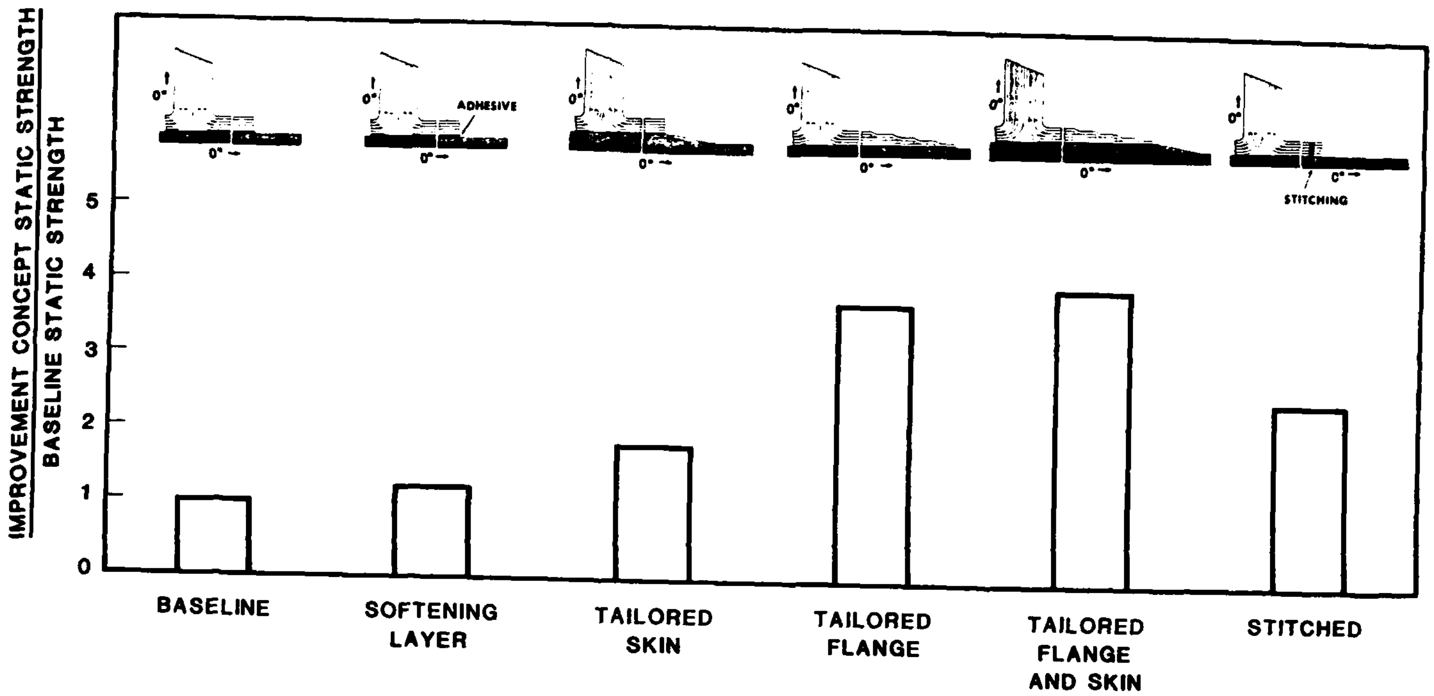

Figure 2.2. Comparison of Static Strength for Several Stiffener/Skin Interface Designs

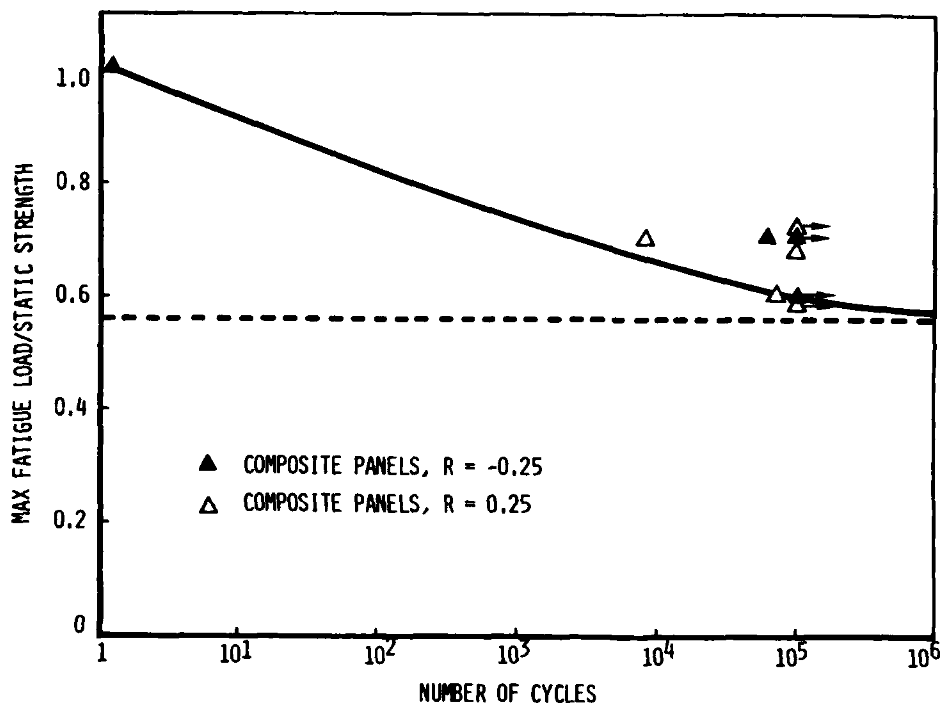

Figure 2.3. Fatigue Data for Curved Composite Shear Panels.

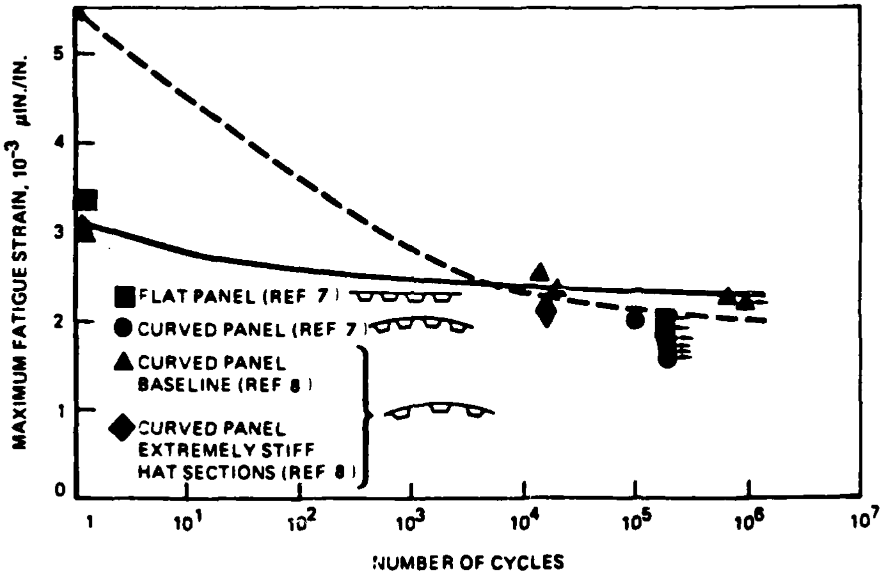

Figure 2.4. Composite Compression Panel Fatigue Response

μin/in. A majority of the postbuckled panels in aircraft applications is stiffness-critical and not strength-critical. The current design practice does not permit the average compressive limit strain in such applications to exceed 3,000 μin/in. Thus, postbuckled composite compression panels are inherently durable at the operating strain levels expected for such applications.

The fatigue behavior of flat composite panels under combined compression and shear loading was investigated in Reference 9. The panels were hat stiffened, made of AS/3501-6 graphite/epoxy. The design represented a fighter aircraft fuselage side panel. The spectrum fatigue test data for these panels are shown in Figure 2.5. The panels were tested for two lifetimes of spectrum fatigue with the maximum load set at 71.6 percent of the static failure load but showed no strength degradation. Constant amplitude fatigue data for flat and curved panels under combined load were obtained in Reference 10, an ongoing study. No fatigue failures were observed and there was no evidence of significant residual strength degradation.

In summary, the durability of flat and curved composite panels under compression, shear and combined loading is clearly demonstrated by the test data available. Thus, fatigue testing of composite panels should be minimized and should be performed only on an as needed basis to validate a specific design requirement .

The influence of environment on static and fatigue behavior of composite panels has been studied in Reference 10. A preliminary analysis of the data in Reference 10 shows that hot/wet environment reduces the initial buckling and failure load in compression by approximately 15 percent. However, the residual strength after constant amplitude fatigue is unaffected. Thus, the influence of environment on the durability of composite panels is not significant.

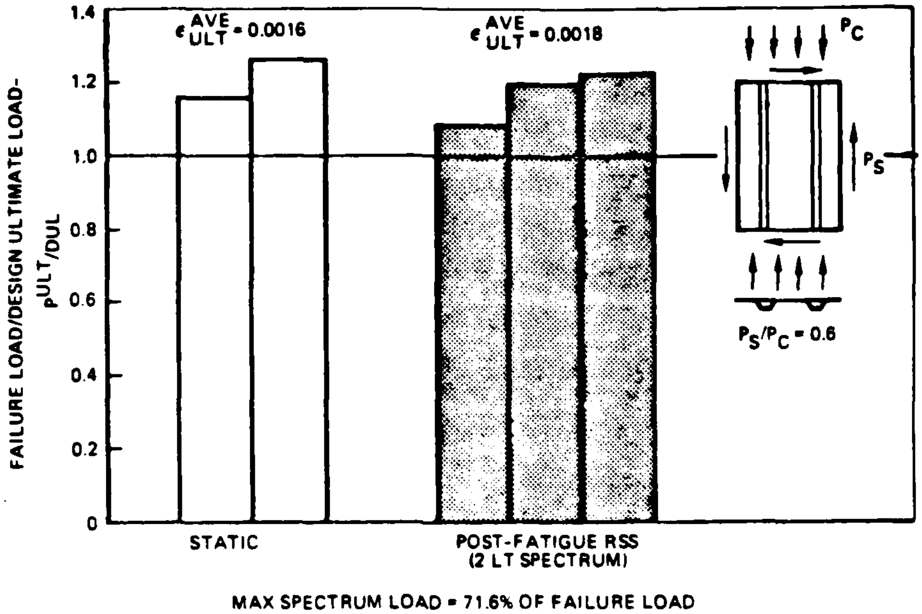

Figure 2.5. Fatigue Response of Flat Panels Under Combined Loading (Reference 9)

2.2 METAL PANELS

The durability of metal postbuckled panels is not as well established. The primary reason for this has been the lack of a comprehensive metal panel fatigue data base. However, the limited data available in the literature and those generated in a recent study (Reference 1) illustrate the fatigue failure modes expected in postbuckled metal panels and the sensitivity of such panels to fatigue crack initiation and propagation.

Fatigue data from a set of early tests on flat metal shear panels (Reference 11) are illustrated in Figure 2.6. These stiffened panels were of a multi-bay configuration as shown in Figure 2.7 and were made of 7075-T6 aluminum alloy. The Z-section stringers and the T-section frames were attached to the web at chem-milled lands. The fatigue tests were performed at an R-ratio of -1. The panels were tested as an eccentrically loaded cantilever beam. In all tests the fatigue crack initiated at a corner of the panel, at the edge of a chem-milled land, and then progressed along the chem-mill line, indicating the effect of the stress concentration at the edge of a chem-milled land. In Figure 2.6 the fatigue lives are plotted as a function of the calculated approximate values of the diagonal tensile stress in the web at the maximum cyclic load. The effect of stress concentration at the land edge is not included in the stress calculation.

Test data for curved metal shear panels were obtained in Reference 1 and are shown in Figure 2.8 along with the data from Reference 11. The 7075-T6 aluminum metal panel configuration and the fatigue failure mode are shown in Figure 2.9. During the fatigue tests on the curved metal panels, cracks were first observed in the skin near the frame attachment fastener holes and near the stringer attachment fastener holes. The cracks adjacent to the stringers were parallel to the stringers and stopped growing shortly after initiation whereas the cracks at the frame fasteners were transverse to the diagonal tension direction and propagated as such across the entire panel. The shear panel fatigue data in Figure 2.8 show that metal panels are sensitive to fatigue and that the operating stress levels for these panels should be at most 40 percent of their static strength to avoid fatigue failures.

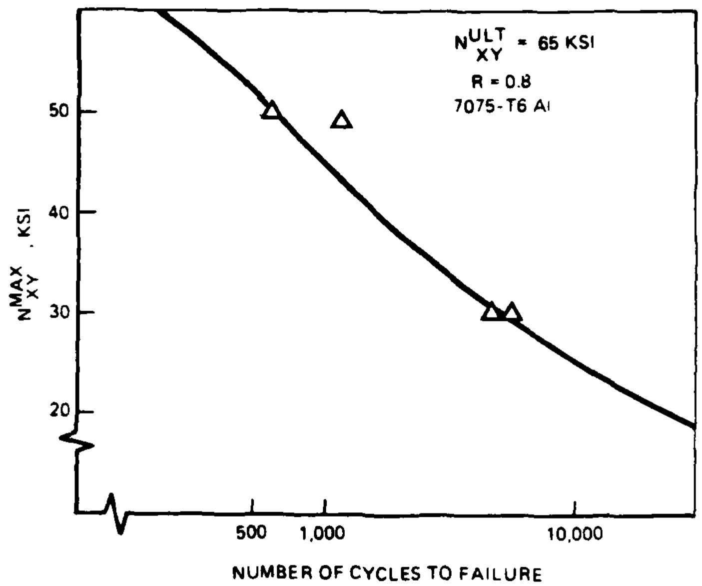

Figure 2.6. Metal Shear Panel Fatigue Data (Reference 11)

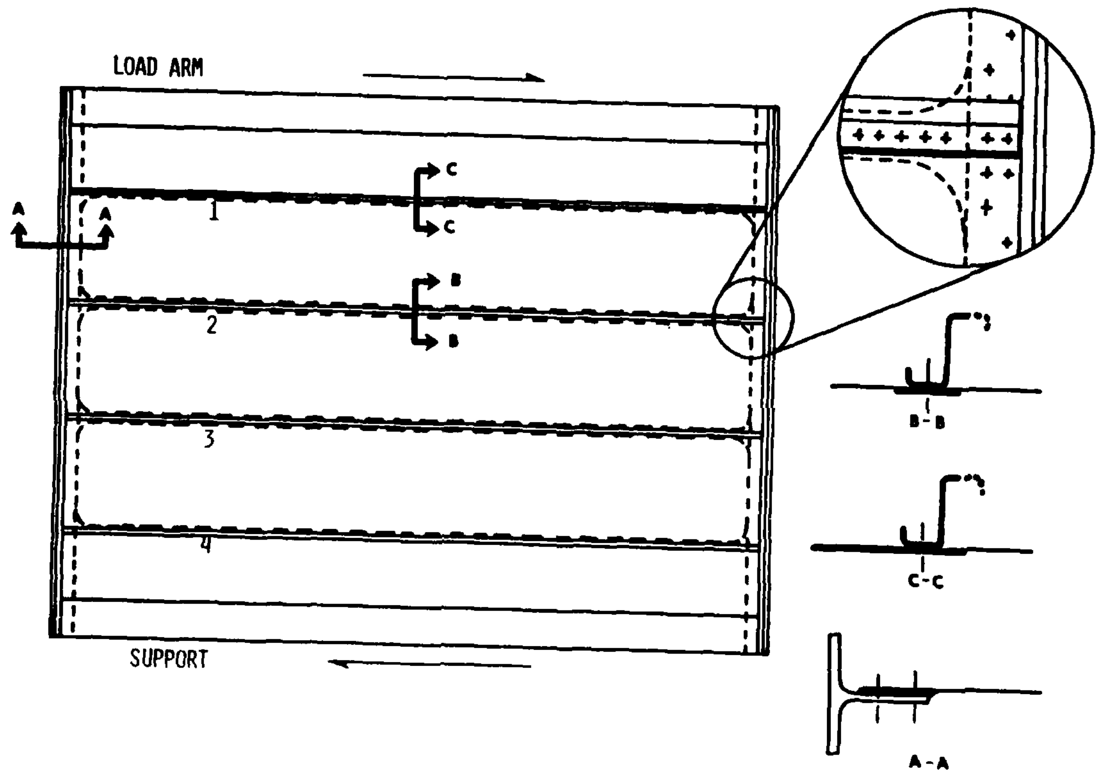

Figure 2.7. Flat Metal Shear Panel Fatigue Specimen (Reference 11).

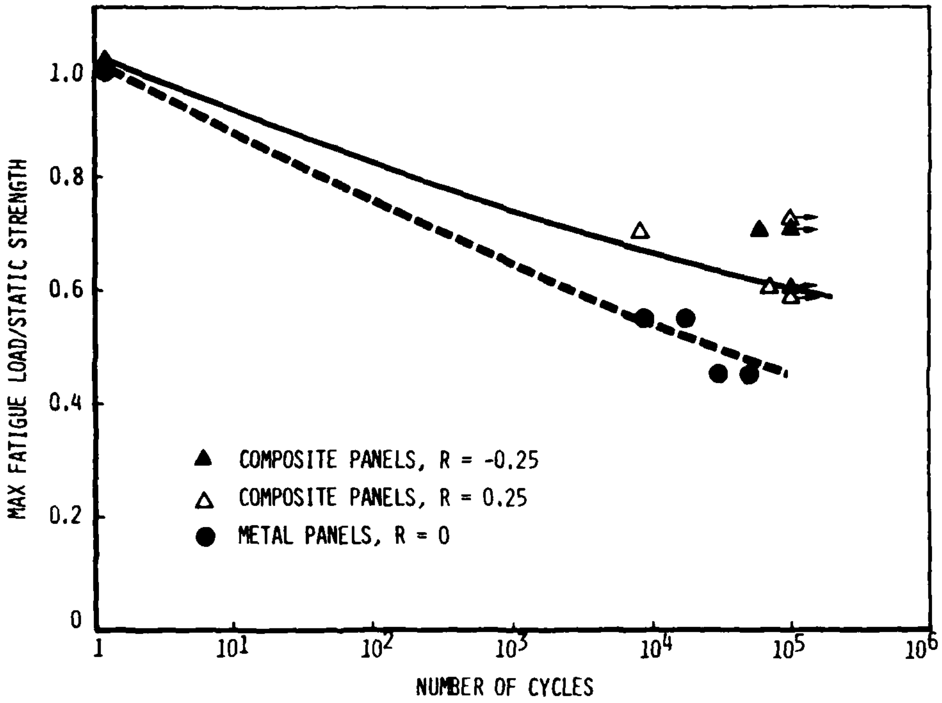

Figure 2.8. Normalized Fatigue Response of Metal and Composite Shear Panels.

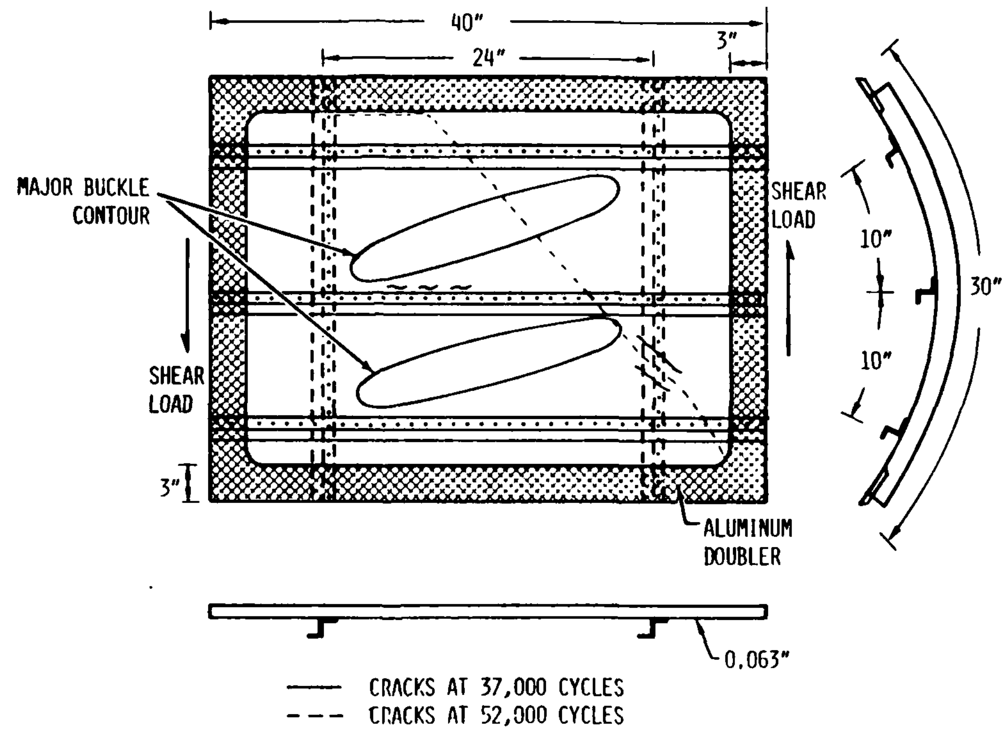

Figure 2.9. Fatigue Failure Mode of Aluminum Shear Panel

Compression fatigue test data for flat stiffened panels loaded in the postbuckling range have been obtained in References 12, 13, and 14. In these panels fatigue cracks occurred in the stiffeners at stiffener attachment fastener holes and propagated along the loading direction as shown in Figure 2.10. The fatigue failure mode, however, is unique to this design. Crack initiation in the skins at these fasteners holes is also possible depending on the local stresses in the skin and in the stiffener.

Compression fatigue tests on curved metal panels were conducted in Reference 1. The fatigue data for these panels are shown in Figure 2.11. For comparison, fatigue data for composite panels designed to the same loads are also shown. The curves have been faired to show the data trend. The tests were conducted under constant amplitude loading and at an R-ratio of 10. The test data are insufficient to select a definitive value for the operating stress levels below which fatigue failures would be unlikely. In these tests, two panels fatigue tested at load amplitudes equal to 66 percent and 55 percent of the average ultimate static strength, developed sizeable skin cracks after only 16,000 and 43,000 cycles of constant amplitude loading, respectively. The cracks were 2.5 inches in length and were located parallel to the stiffeners and along the stiffener edge, away from the fasteners. Such failures have not been previously documented in the literature. A photograph illustrating the fatigue crack pattern in curved metal compression panels is shown in Figure 2.12.

Fatigue data for flat or curved metal panels designed to operate in the postbuckling range under combined loads are not available and need to be generated to identify the fatigue failure modes and the operating stress levels for design. In view of the data for compression and shear panels, fatigue considerations are expected to be design drivers for postbuckled metal panels.

2.3 FATIGUE LIFE PREDICTION METHODOLOGY

A review of the available analysis methods for postbuckled structures (Reference 1) showed that a life prediction methodology for composite

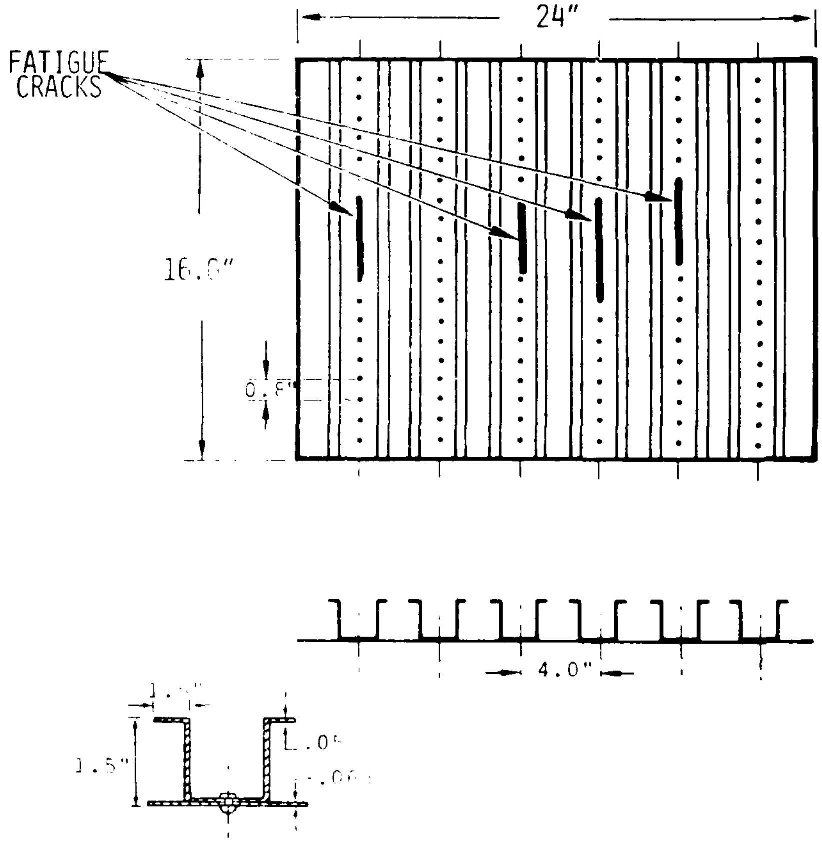

Figure 2.10. Fatigue Crack Preparation in Metal Compression Panels

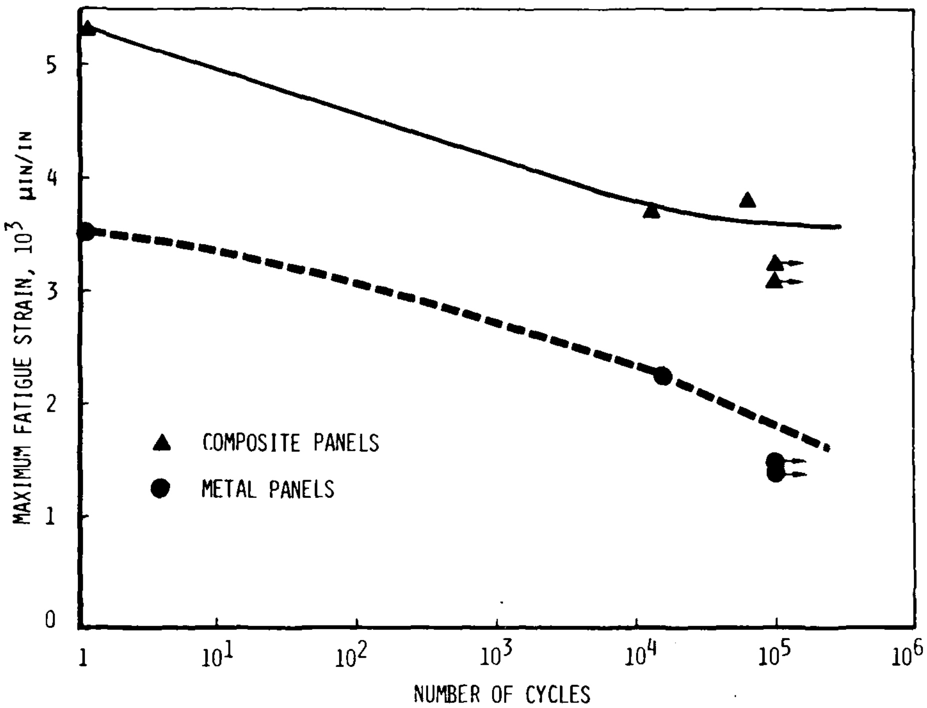

Figure 2.11. Curved Metal and Composite Compression Panel Fatigue Data.

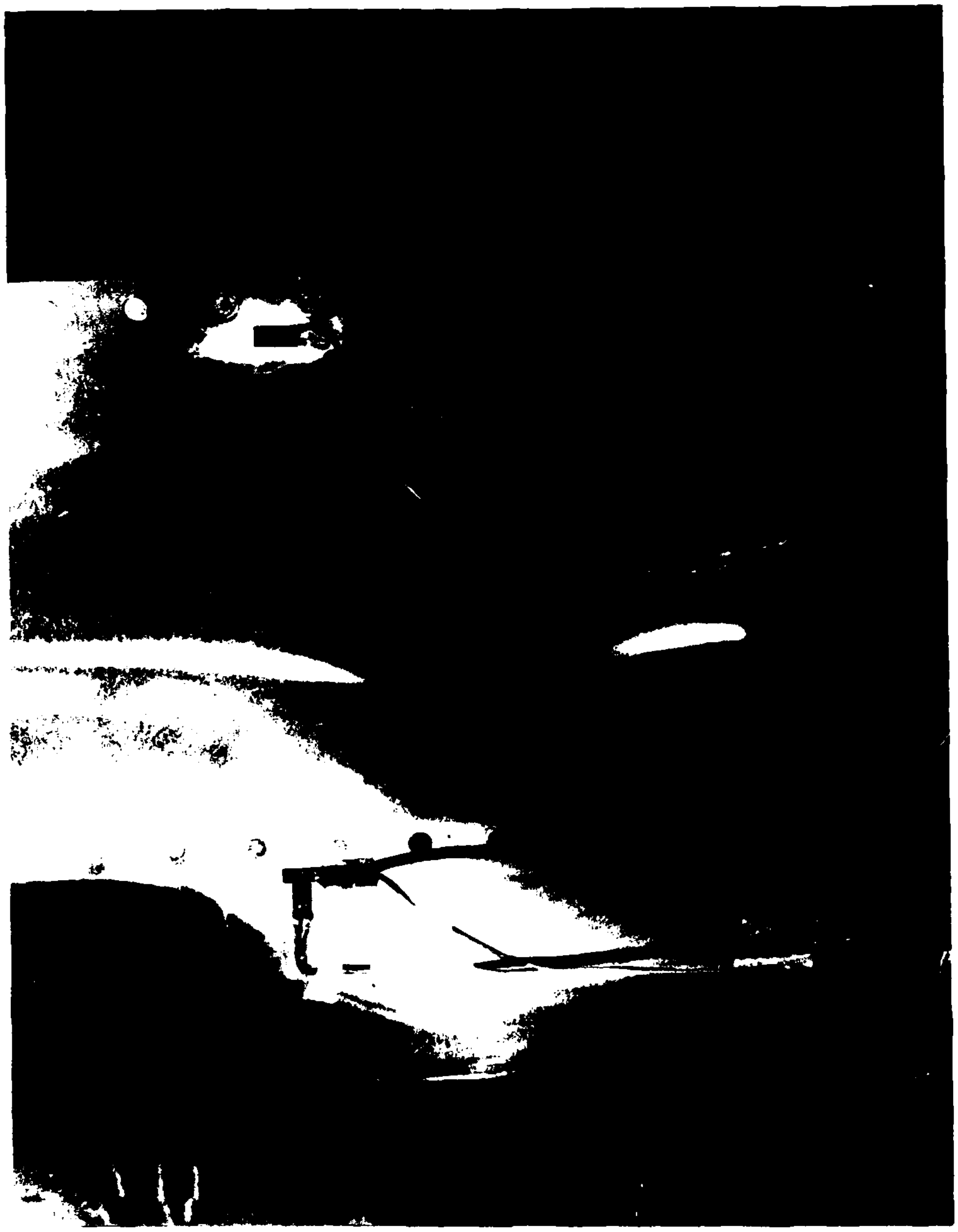

Figure 2.12. Fatigue Crack Pattern in Curved Metal Compression Panels

or metal panels is, at present, not available. This is primarily due to the lack of suitable test data. In Reference 1, based on the observed fatigue failure modes in composite and metal compression and shear panels, two approaches to predicting fatigue life of postbuckled structures have been proposed. The two distinct approaches are essential due to the differences in the failure modes of metal and composite panels. However, prior to application of these methods, several analysis developments are required. In particular, for metal panels under combined loads a methodology to predict the local stresses and stress intensity factors is essential. For composite panels, an analysis to predict the strain energy release rate at the stiffener/web interface, and critical strain energy release rate data are required.

SECTION 3

DAMAGE TOLERANCE OF POSTBUCKLED STRUCTURES

The influence of manufacturing defects and in-service damage on the static strength and fatigue response of postbuckled composite panels has been experimentally investigated in several studies. A majority of these studies was conducted prior to the development of the MIL-PRIME draft damage tolerance requirements (Reference 15). Thus, the defect/damage sizes interrogated in these tests do not exactly match the MIL-PRIME specifications. However, the defect/damage severity is comparable to the MIL-PRIME stipulations. A damage tolerance assessment of the available test data indicates that at the severity levels investigated, composite postbuckled panels are highly tolerant to manufacturing defects and in-service damage at strain levels typical of current designs.

In contrast to the sizeable damage tolerance data base for composite panels, postbuckled metal panel design compliance with MIL-A-83444 has not been investigated. This is primarily due to the lack of a fatigue analysis methodology for postbuckled metal panels and substantiating test data.

The postbuckled composite panel test data are presented and discussed in the following subsections.

3.1 SHEAR PANELS

The influence of a skin stiffener disbond was studied in Reference 16 for postbuckled shear panels where a disbond was simulated by a teflon embedment. Several panels were tested with these embedded disbonds at the skin/stringer interface. A majority of the panels with disbonds demonstrated no significant growth of the disbond nor a loss in strength or fatigue life. In the isolated worst case shown in Figure 3.1, growth of the disbond from 2.0 inches to 4.0 inches did occur after 100,000 cycles accompanied by a strength loss of about 16 percent. However, the test conditions were far more severe than would be encountered in actual design

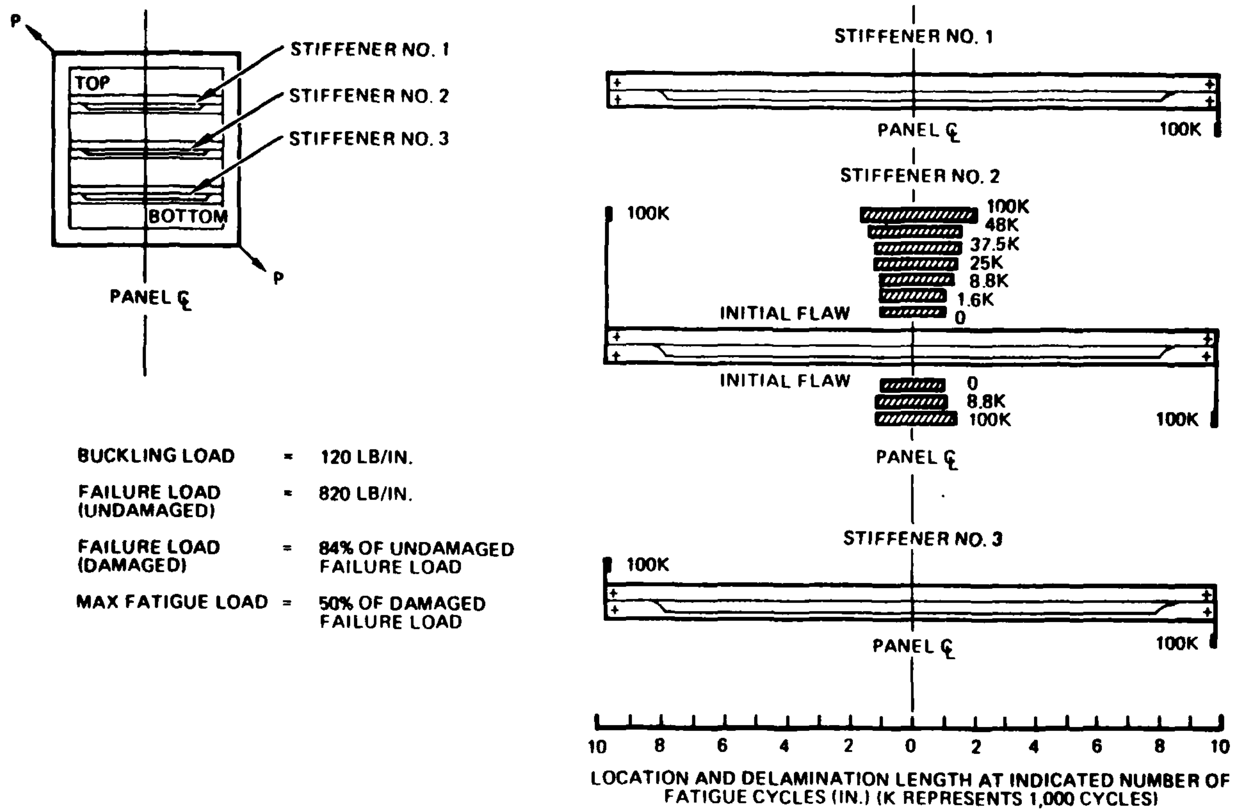

Figure 3.1. Influence of Skin-Stiffener Disbond on Shear Panel Fatigue Strength (Reference 16)

practice.

The effect of clearly visible impact damage on postbuckling strength of composite shear panels is summarized in Figures 3.2 and 3.3. These data are taken from References 3 through 6. The data in Figure 3.2 show that impact damage of the severity evaluated had no significant effect on the initial global buckling or the ultimate failure loads. The fatigue data shown by solid symbols in Figure 3.3 illustrate that the fatigue life of clearly visible midbay impact damaged panels is not significantly affected by the impact. These data were obtained from References 3 and 5. From the unshaded symbol data, if the design details were not known, it would appear that impact damage does significantly reduce fatigue life. However, the data point (Figure 3.3) shown by the unshaded diamond, was obtained from tests on a panel with an extremely high level of porosity at the stiffener/web interface and is not representative of typical composite panels. Secondly, the blade/flange impact data (Figure 3.3) shown by unshaded squares, show a significant amount of scatter which may be due to fabrication variability at the skin stiffener interface. Considering these aspects of the various tests the data trend shown by the solid line appears to be the most probable. On the basis of the data trend, therefore, it appears that the fatigue endurance limit for postbuckled composite shear panels is at least the design limit load. Additional data are required, however, before this conclusion can be confirmed.

3.2 COMPRESSION PANELS

The damage tolerance of composite compression panels loaded beyond their initial buckling load is presented in Figures 3.4 through 3.7. These data were taken from References 7 and 17. In Figure 3.4, the results of studies on panels impacted at different locations while loaded in compression are presented. It can be seen from this figure that the failure strain of panels with impact damage is at least 2,500 μinches/inch under all conditions. More important is the fact that for panels with any significant postbuckling strength the failure strain increases. This aspect of the data is more clearly illustrated in Figure 3.5 where the post-impact compression

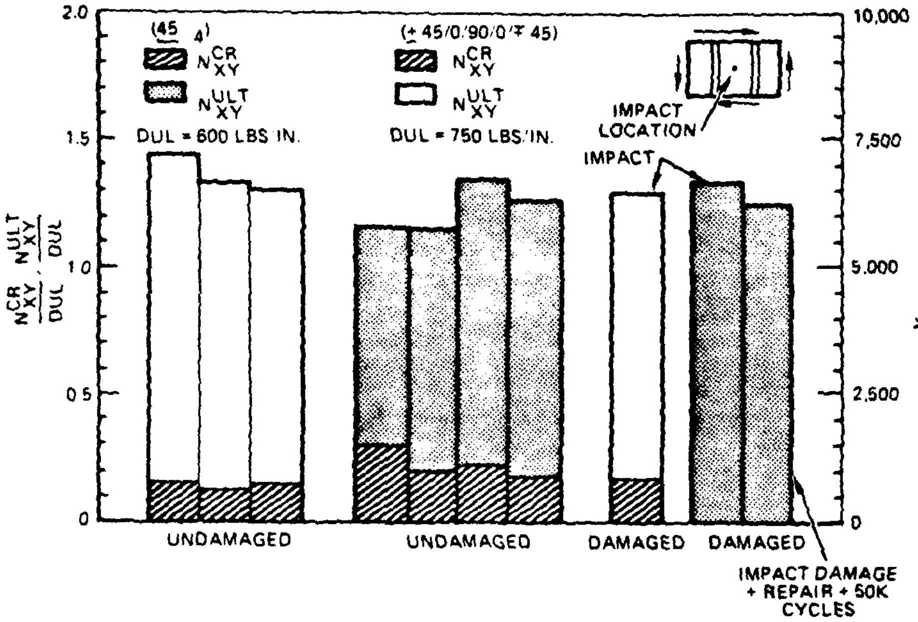

Figure 3.2. Influence of Impact Damage on Shear Panel Static Strength (References 3 and 5)

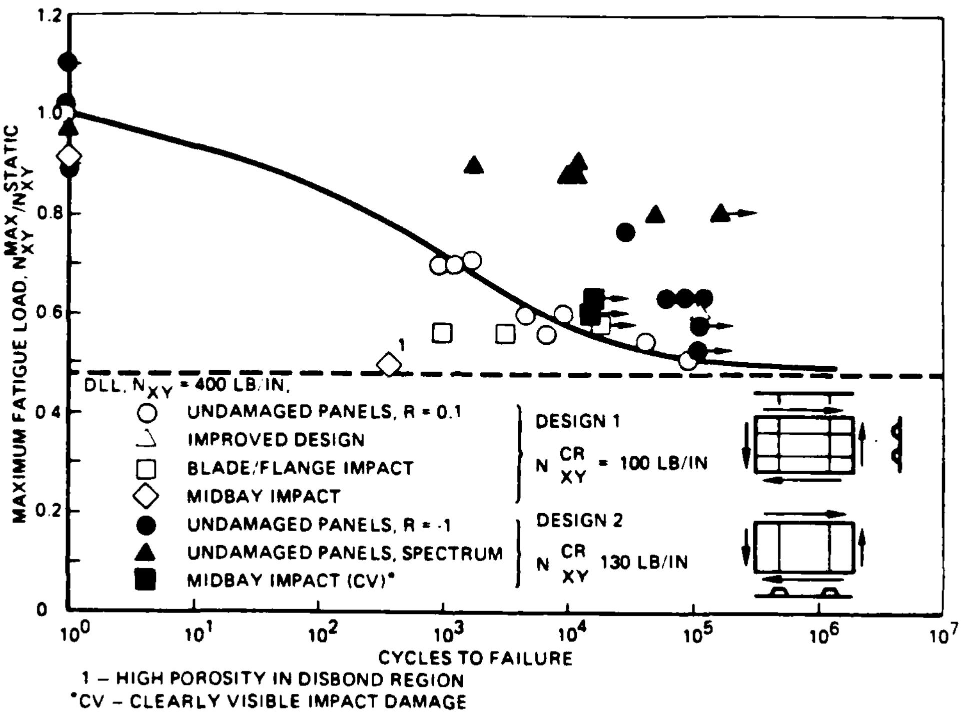

Figure 3.3. Influence of Impact Damage on Shear Panel Fatigue Response (References 3 thru 6)

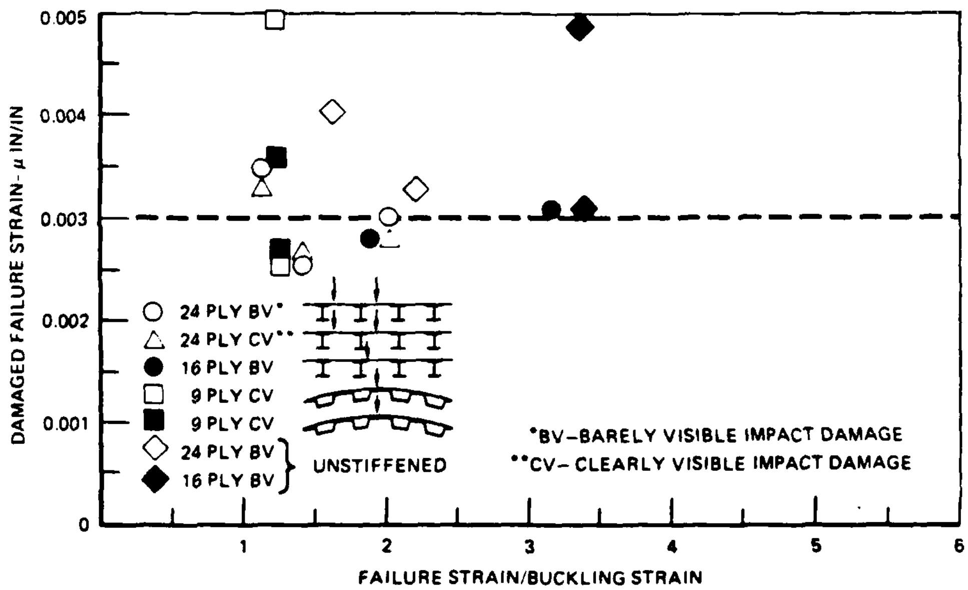

Figure 3.4. Influence of Impact Damage on Composite Compression Panels (References 7 and 17)

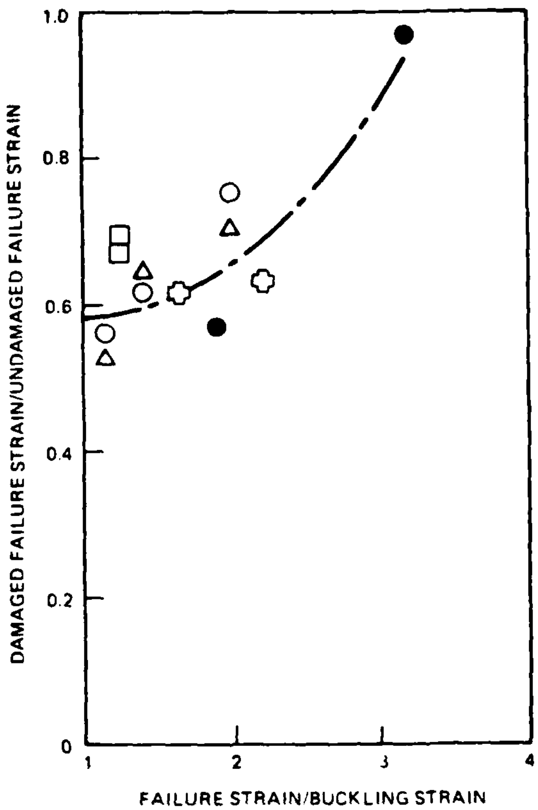

Figure 3.5. Normalized Influence of Impact Damage on Composite Compression Panels (Reference 17)

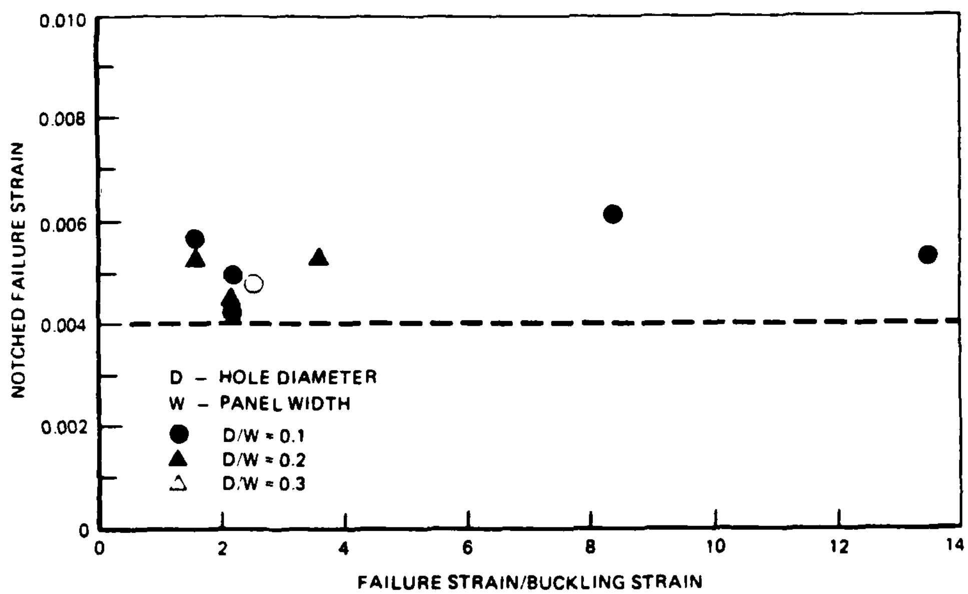

Figure 3.6. Influence of Holes on Composite Compression Panels

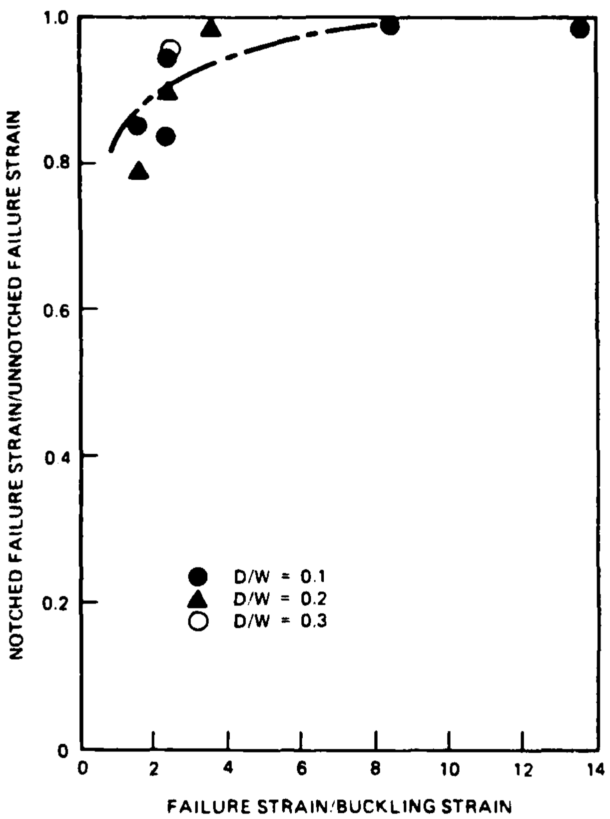

Figure 3.7. Normalized Influence of Holes on Compression Panel Static Strength (Reference 17)

ultimate strain is seen to increase as the postbuckling ratio increases.

The influence of fastener holes on postbuckled composite compression panels is shown in Figures 3.6 and 3.7. These data were taken from Reference 17. From Figure 3.6 it is evident that for holes as large as one-third the bay width, the ultimate strain in compression is no less than 4,000 μin/in. This minimum value of the failure strain is considerably higher than typical design values of around 2,500 μin/in. In addition, it should be noted from Figure 3.7 that the influence of fastener holes diminishes as the postbuckling ratio increases.

3.3 COMBINED COMPRESSION AND SHEAR LOADING

Damage tolerance test data for composite panels under combined loading are extremely limited. Test data to determine the influence of porosity on flat postbuckled panels under combined loading were obtained in Reference 9. The effect of severe porosity (4 percent by chemical analysis) on these hat stiffened AS/3501-6 panels loaded in combined compression and shear was shown to be insignificant. This fact is illustrated by the data shown in Figure 3.8.

Additional data are required to determine the influence of impact damage on the static strength and fatigue life of flat and curved panels under combined loads.

The available data on compression and shear panels, however, indicate that postbuckled composite panels can sustain relatively severe damage without functional impairment. The additional tests recommended should be performed only to confirm the trends indicated by the data.

3.4 REPAIRS

The feasibility and adequacy of conventional repairs (Reference 18) for composite panels have been investigated in References 7 and 19. In Reference 7, AS/3501-6 compression panels with mid-bay impact damage were repaired using a flush patch and statically tested. A photograph of the repaired compression panel is shown in Figure 3.9 The repaired panel static

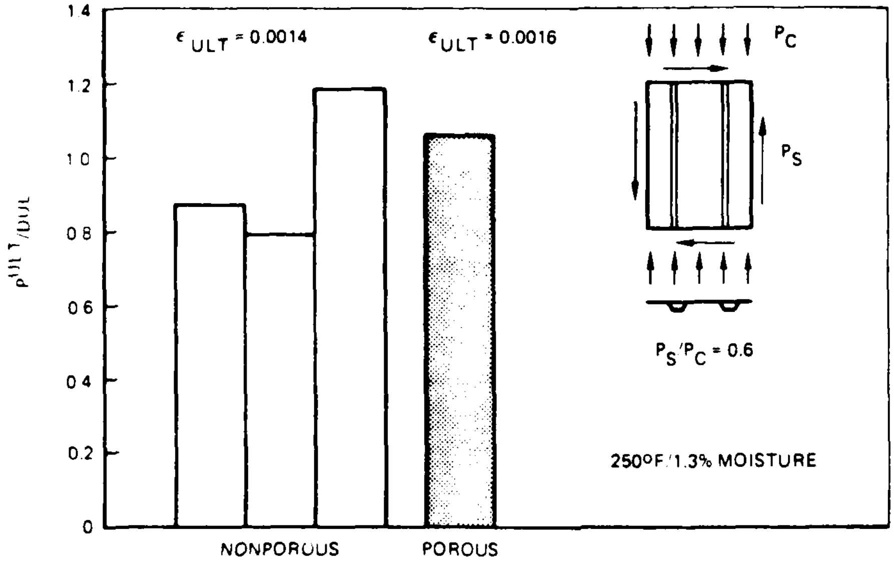

Figure 3.8. Influence of Porosity on Flat Composite Panels Under Combined Loading (Reference 9)

test data showed no significant strength reduction as compared to the undamaged panels. The failure was away from the repair area in one of the end stiffeners as shown in Figure 3.9. The only difference in panel behavior was that the end bay webs exhibited significant buckling similar to undamaged panels, but the out-of-plane web displacements for the repaired bay were not as prominent as in the undamaged panels.

Repairs of stiffeners and stiffener/skin disbonds in shear panels were performed in Reference 19 where a previously static tested and failed flat shear panel was repaired and re-tested. Panel failure in the initial test was by complete separation of the stiffener from the skin accompanied by extensive skin surface delamination. The repairs were performed by applying a scarfed patch to the delaminated skins and by adhesively bonding the stiffeners. A photograph of the repaired shear panel is shown in Figure 3.10. Static test of the repaired panel showed no loss in strength thus demonstrating the integrity of the repair.

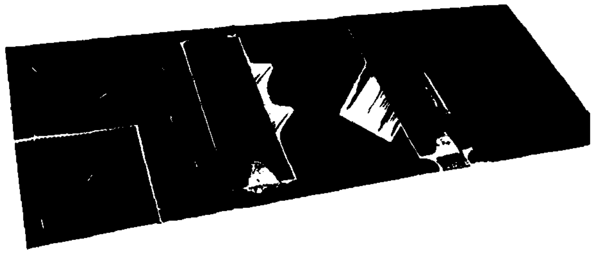

Figure 3.9. Failure Mode of Repaired Compression

Figure 3.10. Shear Panel After Repair (Reference 19)

SECTION 4

RECOMMENDED FUTURE WORK

4.1 SUMMARY

The excellent durability and damage tolerance of composite panels under shear or compression loading and their damage tolerance under combined loading is substantiated by the existing data base. However, the durability of composite panels designed to operate under combined loads needs to be confirmed. The available data also show that the durability of metal panels designed using available analyses appears to be in question. Additional data on the fatigue life of metal panels under combined loading are required. These data will be useful in identifying fatigue failure modes for metal panels under combined loads. Analysis techniques to verify metal postbuckled panel damage tolerance and compliance with MIL-A-83444 also need to be developed.

Available data indicate that the repair techniques for buckling resistant structures can be used to repair postbuckled composite panels and restore panel strength to almost 100 percent of its undamaged strength.

4.2 DATA GAPS

As a result of this technology assessment, specific data and analysis requirements that must be addressed to make postbuckling viable for future aerospace vehicles have been identified and are summarized in Table 4.1. The most significant data gap is in the area of metal panel fatigue under combined loading. Test data need to be generated for curved metal panel designs representative of actual aircraft fuselage structures. Using the results of these tests a life prediction methodology for postbuckled metal panels needs to be developed.

For composite panels under combined loading, a limited number of fatigue tests have to be conducted to confirm the durability characteristics observed in the case of panels under compression or shear loads. The fatigue load levels in these tests must be severe enough to force failures so that

TABLE 4.1. SUMMARY OF DATA GAPS IN THE DURABILITY AND DAMAGE TOLERANCE TECHNOLOGY OF POSTBUCKLED METAL AND COMPOSITE STRUCTURES

TECHNOLOGY	COMPOSITE PANELS	METAL PANELS
DURABILITY	Fatigue test data for curved composite panels under combined loads. Influence of R-ratio; Influence of shear to compression load ratio. Identify fatigue failure modes under combined loading and obtain S-N data. Analysis Methodology to predict strain energy release rate for disbond growth at the stiffener/web interface. Simple tests to measure critical strain energy release rate and disbond growth rate as a function of the strain energy release rate.	Fatigue test data for curved metal panels to identify fatigue failure modes and generate S-N curves. Influence of combined load ratio on fatigue behavior. Life prediction methodology for curved and flat panels under combined loading.
DAMAGE TOLERANCE	Influence of impact damage under combined loads - Mid-bay location - Over stiffener location	Analyses for compliance with MIL-A-83444

the failure modes can be identified. Since stiffener/web separation is the expected failure mode in the fatigue tests on composite panels, an analysis methodology to predict the propagation of an initial flaw at the interface is required. The specific approach that can be used for this purpose consists of analytically computing the strain energy release rate at the initial flaw tip due to the applied loading and using it in conjunction with a non-linear law and the material properties to predict growth of the disbond.

To complement the existing data base on the damage tolerance of composite panels a limited number of static tests on impact damaged panels need to be conducted. The impact damage in these tests should be introduced at the most critical location which is expected to be over a stiffener flange bonded to the skin.

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